Digital Implementation of Convolutional Code-Based Spread Spectrum Low Power Transmitter

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ABSTRACT

In this paper, we explore how pulse shaping and digital coding affect power consumption in transmitter circuits. We implement and evaluate an Ultra Wide Band (UWB) Manchester pulse shaper and convolutional encoder. We compare Manchester pulse shaping with typical root raised cosine (RRC) pulse shaping used in narrow band (NB) systems. We also evaluate the potential of channel coding to gain transmission power savings. We show that our proposed technique can potentially yield orders of magnitude savings in power consumption. By using Manchester pulse shaping, we save three orders of magnitude in power over RRC shaping. Similarly, by investing 1μW to signal processing to perform coding, we gain an order of magnitude in effective transmission power.

1. INTRODUCTION

NB systems require confinement to a spectrum allocated by the FCC. In this paper, we propose the use of an UWB system by spreading the spectrum using both a low rate convolutional code as well as square pulse shaping seen in digital signals. With enough spreading and coding gain, we can transmit and receive a wideband signal that appears in the noise floor of other systems in the RF spectrum while still meeting the requirements of UWB regulations stipulated by the FCC.

We use a typical convolutional code to obtain coding gain, which allows us to lower our transmit power as well as meet UWB communications requirements. Figure 1 shows a block diagram of the proposed transmitter, and Figure 2 shows a corresponding receiver. This is just a simple receiver. Higher performing receivers are also possible at a cost of greater complexity. In contrast, the transmitter shown in Figure 3 shows the typical design of an RRC-based narrowband transmitter.

Using these techniques, we explore how we can cause changes in lower-level circuit behavior by changing high-level communications architecture. As we discuss in our Experimental Results, we show that Manchester pulse shaping combined with convolutional encoding shows promise in being able to simplify a transmitter and save a substantial amount of power.

2. APPROACH

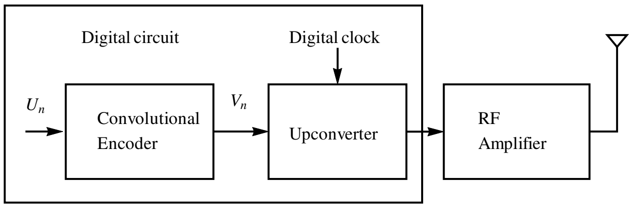

Figure 1: System Model

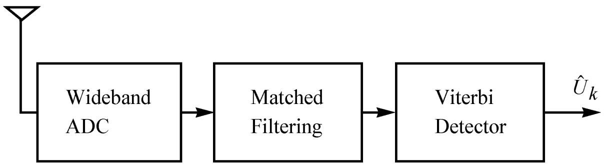

Figure 2: UWB Receiver Model

We investigate the power consumption of different components of a digital communications transmitter by implementing and simulating them. In cases where circuits are too complex, we simulate scalable representations of signal processing circuitry and interpolate results.

The simple Manchester pulse shaping circuit was implemented by hand. We synthesized the more complex circuits from VHDL. As we describe below, we implemented a digital root raised cosine pulse shaper and a digital convolutional encoder. We generate netlists with the Cadence RC tool, then import the netlists into Cadence in order to simulate their analog behavior.

2.1 Assumptions

In brief, we attempt to simplify the design of a transmitter in order to lower its power consumption. We assume that the transmitter is power-constrained, whereas the receiver is not. This makes sense in applications such as body sensor networks, in which each transmitter has a power budget on the order of μW. On the other hand, we assume that the receiver is not power constrained, and can thus afford increased complexity that may be required to process incoming UWB signals.

2.2 Symbol Mapping and Pulse Shaping

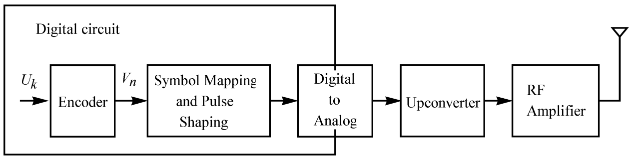

Figure 3: RRC Narrowband Transmitter Model

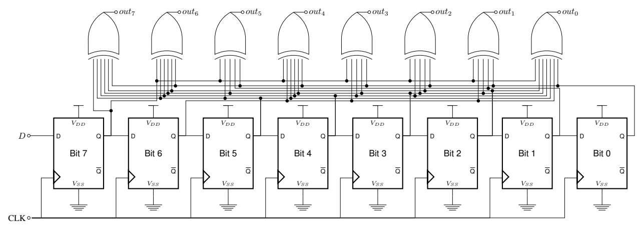

Figure 4: The convolutional encoder RTL schematic. It is based on a shift register with a characteristic polynomial taken from [4].

In a typical Quadrature Amplitude Modulation (QAM) transmitter, the encoded bits V_k are mapped to an alphabet of symbols on the complex plane. This sequence are then pulse shaped by convolution with a pulse shaping filter. We investigate the power needed for this operation by simulation.

We implement a 12-bit root raised cosine (RRC) pulse shaper as a basis for comparison with regard to power consumption. This consists of a shift register and adders to sum incoming symbols together scaled by an RRC filter. Naturally, a DAC would be required after this operation in a true narrowband system, as seen in Figure 3.

2.3 Forward Error Correction

In Figure 1 the data source bits U_n are coded by a forward error correction (FEC) encoder to get the encoded bits V_n. In low power communications, there is a tradeoff between the coding gain achieved by FEC and the power needed to implement the signal processing. The coding gain allows the transmit power to be lowered as the receiver is able to decode the message at a lower signal to noise (SNR) threshold. For example, if the FEC achieves a coding gain of 6dB, then the transmit power can be lowered by that amount (4X savings in this case).

In a typical symmetric two-way communications system, the tradeoff between the processing power needed for FEC signal processing and transmit power is a legitimate concern. However, in the asymmetric configuration we consider, FEC seems to be an obvious choice since the complexity of the FEC signal processing is typically located at the receiver.

In our investigation of FEC, we begin with a convolutional encoder. Basic convolutional encoding is not in the same class of performance as modern capacity-approaching codes such as Turbo Codes or Low Density Parity-Check Codes (LDPC). However, it is very simple to implement at the transmitter, and an extrapolation of power consumption to Turbo Codes should be straightforward in future work. Figure 2.3 shows the register transfer level (RTL) schematic used to simulate convolutional encoding.

2.4 Simplified Low Power Transmitter

We propose a new low power transmitter that, to our knowledge, has not been thoroughly investigated. We seek a purely digital solution from the baseband up through the passband, requiring only an RF amplifier. In a typical digital communications system, the baseband is upconverted to the passband and amplified by analog RF components, as seen in Figure 3. Here, we try to use the digital clock of the system to digitally upconvert a binary baseband signal such that minimal analog components are necessary, which would mainly be only the RF amplifier. Furthermore, in many wireless systems, an RF amplifier is biased to operate in the linear region. However, our design allows the RF transmitter to operate in saturation. As the output is essentially square waves, nonlinear characteristics of such an amplifier is not a concern. Consequently, further power savings emerge since, theoretically, the entirety of the amplifier's DC power is used to transmit the digital signal. In contrast, linearly biased amps would dissipate 50% of the power as heat.

Normally, narrowband systems require that signals be confined to a spectrum allocated by the FCC. However, our design spreads the signal over a wide spectrum via convolutional codes and Manchester pulse shaping. With enough spreading and coding gain, we can transmit and receive a wideband signal that appears in the noise floor of other systems in the RF spectrum, and meet the requirements of ultra wide band (UWB) regulations as stipulated by the FCC.

We use a typical convolutional code [4] to obtain a coding gain, which, as discussed in our Results section, allows us to lower our transmit power while still meeting the FCC requirements for UWB communications, and also maintaining our desired symbol rate.

There is a potential to save power by replacing the RF mixer and local oscillator by a digital domain upconversion, which consists simply of an XOR operation between the digital baseband signal V_n and the digital clock (e.g., Manchester pulse shaping).

3. EXPERIMENTAL RESULTS

We studied the power consumption related to pulse shaping and channel coding by implementing the transmit signal processing of these subsystem in hardware.

3.1 Manchester Pulse Shaping

To compare the complexity and power usage of UWB Manchester pulse shaping with NB RRC pulse shaping, we designed and implemented both signal processing operations.

The Manchester pulse can be implemented by the XOR of the transmit bits with the clock. In our implementation we followed the XOR gate with two inverters to remove glitching. This is important since the output will be used to drive a power amplifier (PA) in a switched mode. Therefore it is important that the waveform looks like a clean square wave,

Table 1: Comparison of Manchester and RRC Pulse Shaping

Pulse Shaping	Implementation	Amp DC Power (μW)	Amp TX Power (μW)	Gates	Clock Speed (MHz)	Processing Power (μW)	Timing Slack
Manchester	CMOS XOR 1.1V	24	24	3	400	6.75	19.96ns
Manchester	CMOS XOR 500mW	24	24	3	400	1.11	
Manchester	TX Gate XOR 1.1V	24	24	3	400	3.66	
Manchester	TX Gate XOR 1.1V	24	24	3	400	0.56	
RRC	CMOS 1.1V	48	24	1132	400	604	614ps
RRC	CMOS 1.1V	106	53	1122	50	498	18μs

and not just a digital signal that is able to meet the setup and hold times of the next sequential element.

We experimented with different implementations of the XOR gate, and found that the transmission gate version expends about half the amount of power as the CMOS implementation, while giving an output waveform that looks the same. To save power, we turned down the supply voltage, and found that the waveform still looked good at a supply voltage of 0.5V. At 250 mV, the waveform began to loose it's square features. The ratio of the pulse widths of the Manchester encoded signal also began to distort.

In an attempt to combat this, we experimented with sampling the output of the XOR with a single edge register at twice the clock rate, as well as a dual edge register at the same clock rate. However the output of the register did not improve the shape of the pulse, and in some cases the waveform would not latch properly at 250 mV. Figure 5 shows the simulated power consumption of the Manchester pulse shaper as the nominal V_{dd} is scaled down.

It is interesting to note that although the CMOS based XOR draws more power, it maintains the proper pulse widths down to 300 mV, while the transmission gate XOR does not.

3.2 Root-Raised Cosine Pulse Shaper

We synthesized a RRC pulse shaping circuit from VHDL. Pulse shaping is basically a convolution operation, and can be represented as a matrix multiplication of a matrix representing the pulse shape with a vector representing the current and past symbols held in a shift register. This operation occurs at each symbol period. In our implementation we used a 12-bit two's complement representation of the pulse stored in an 8-by-8 matrix. The shift register contains 8 binary symbols which represent +1 and -1 in the matrix multiply. The output is a 12-bit two's complement vector which is typically converted by a DAC to an analog baseband and upconverted to the passband before amplification and transmission.

The synthesis produced a result with over a thousand gates. We first compared the power draw at the same clock rate as the UWB system, but this is not a fair comparison since most NB systems run at a much lower symbol rate. So we did a comparison at 50 MHz, which would produce a bandwidth of 50 MHz, which is still rather high. However doing so did not lower the power by that much at 1.1 V. In the last row of the table, we tried to shift the power saved by lowering the clock speed to the transmitter, but because the

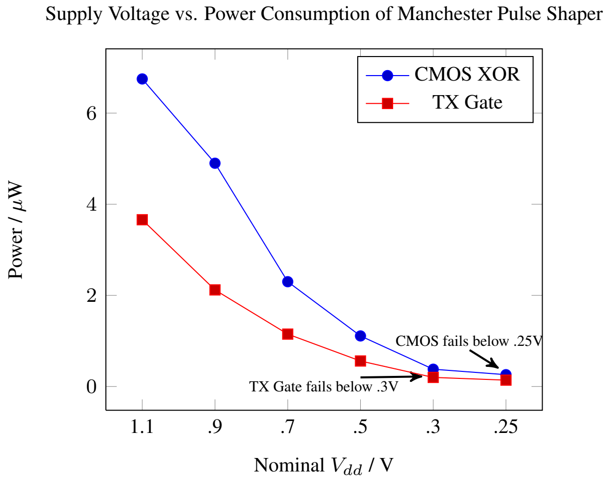

Figure 5: Power consumption of Manchester pulse shaper.

linear transmitter for a RRC is around 50%, the increase in transmit power is only by 50% of the power savings. Even if V_{dd} were reduced to obtain a quadratic savings in power, only half of this power could be realized as actual transmit power.

Table 1 summarizes the simulation results comparing the two pulse shaping techniques. Manchester coding provides a large amount of slack which we can use to scale down voltage while still retaining the target symbol rate (i.e., a clock rate of 400MHz).

3.3 Convolutional Encoding

We also synthesized a convolutional encoder in VHDL. This consists of a shift register, 8 bits long, with an 8-bit output formed from a characteristic polynomial derived from [4]. The encoder was functional when its V_{dd} scaled down to 250mV, at which point it drew less than 1μW of power. However, this simple encoding scheme yields a 6dB (roughly 4.5X) coding gain, meaning we can achieve the same performance with coding if we scale power consumption down by 4.5X. Thus, by paying 1μW in processing to code input, we can transmit with more than 4X less power and still achieve the same symbol rate. Figure 6 shows the power consumption of the encoder as the nominal V_{dd} is scaled down.

what the other nodes are doing. The receiver in this case is able to distinguish the different transmitters by their different pseudorandom spreading sequences.

We have also shown that convolutional encoding can be implemented very efficiently in hardware and that coding definitely has its place in the asymmetric communications scenario we are considering.

A very preliminary pathloss study shows that our proposed scheme with Manchester pulse shaping and convolutional encoding are applicable to body area network (BAN) applications, and can support a maximum date rate of 50 Mbps at a transmit power of 24 μ W. The pathloss requirement for BAN operation was taken from [1]. The pathloss measurements quoted there were at 2.4 GHz, so the actual pathloss at 400 MHz will be considerably smaller. The weakest assumption in our calculations is an antenna gain of -10 dB. There has been work in wideband miniaturized antennas [5] in our band of interest, but actual experimentation would be the best way to determine the effect of antenna gain.

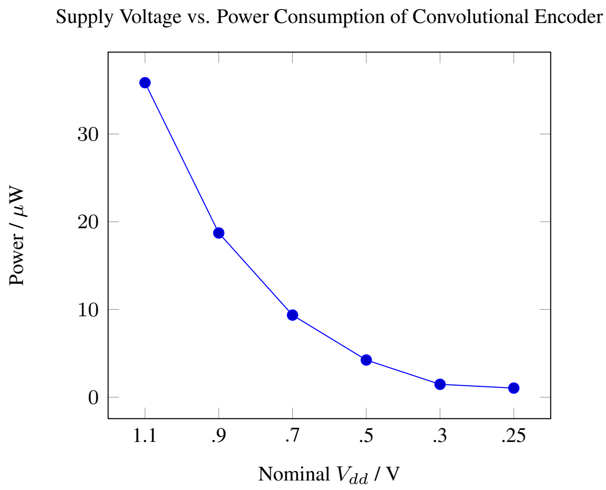

Figure 6: Power consumption of convolutional encoder.

4. CONCLUSION

We have shown that there are considerable power savings available when we tune communications system design at the upper layers which in turn affect the lower circuit and device layers. In particular, we have shown that UWB Manchester pulse shaping not only allows a the power amplifier to operated in a switched mode, but also is very simple to implement. Although it known that UWB signals can be generated efficiently from digital circuitry which allows the power amplifier to avoid power dissipation due to static bias current [3], it seems there has not been much research in the use of Manchester pulse shaping for this purpose. Furthermore it seems that the other digital based transmission schemes are much more complicated. It certainly would be difficult to beat the simplicity of Manchester pulse shaping as it only requires an XOR gate. One disadvantage of the scheme reported in [2] is that the proposed pulses contain spectral lines which limits the power output under FCC regulations. The Manchester pulse does not produce spectral lines and would theoretically be able to transmit at a higher power as allowed by the FCC.

Manchester pulse shaping falls under the auspices of binary antipodal signalling and binary phase shift keying (BPSK), which has a 3 dB advantage over basic on-off keying (OOK), which is commonly used in UWB communications. Although there are derivatives of OOK that rival and surpass BPSK in power efficiency [6], BPSK based schemes mesh nicely with Direct Sequence Spread Spectrum (DSS) techniques that provide not only interference rejection but also a very convenient form of rate throttling under different pathloss scenarios. Furthermore, DSS can be implemented as an XOR of the data sequence with a pseudorandom sequence, which can be generated by a structure very similar in complexity to the convolutional encoder. DSS can also be used in a multiple access scheme which is known as Code Division Multiple Access (CDMA), which allows simultaneous transmission over the same frequency band. This may allow for simplified media access control where the transmitter can simply transmit when there is data and not worry about

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] B. H. Calhoun, J. Lach, J. Stankovic, D. D. Wentzloff, K. Whitehouse, A. T. Barth, J. K. Brown, Q. Li, S. Oh, N. E. Roberts, et al. Body sensor networks: A holistic approach from silicon to users. *Proceedings of the IEEE*, 100(1):91–106, 2012.

[2] J. R. Fernandes and D. Wentzloff. Recent advances in IR-UWB transceivers: An overview. In *Circuits and Systems (ISCAS), Proceedings of 2010 IEEE International Symposium on*, pages 3284–3287, 2010. ID: 1.

[3] Y. Park and D. D. Wentzloff. IR-UWB transmitters synthesized from standard digital library components. In *Circuits and Systems (ISCAS), Proceedings of 2010 IEEE International Symposium on*, pages 3296–3299. IEEE, 2010.

[4] J. Proakis. *Digital Communications*. New York, NY: McGraw-Hill, 2008.

[5] A. Raslan and A. Safwat. N-internal port design for wide band electrically small antennas with application for uhf band. *Antennas and Propagation, IEEE Transactions on*, 61(9):4431–4437, 2013.

[6] Q. Tang, S. K. Gupta, and L. Schwiebert. BER performance analysis of an on-off keying based minimum energy coding for energy constrained wireless sensor applications. In *Communications, 2005. ICC 2005. 2005 IEEE International Conference on*, volume 4, pages 2734–2738. IEEE, 2005.